German-Dutch Wind Tunnels

The Higher-Harmonic Control Aeroacoustic Rotor Test (HART) in the DNW-LLF

Final Technical Report
by

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Introduction

With increasing use of helicopters the problem of noise emission of helicopters became more and more important. The first HART program on rotorcraft noise has shown that blade vortex interaction (BVI) is a major source of impulsive noise. As BVI-noise is generated by the induced velocities of tip vortices, it depends on vortex strength and miss-distance, which itself depends on vortex location and orientation and convection speed relative to the path of the advancing blade. The detailed study of these vortices by means of Particle Image Velocimetry (PIV) and by means of flow visualization with the Laser Light Sheet method (LLS) is of particular interest for progress towards quieter rotorcraft and is the subject of this program.

For a detailed analysis of blade vortex interaction it is also essential to gain some knowledge about the deformation of the rotor blades due to aerodynamic loading at different azimuth angles. For this purpose DNW developed a dedicated photonical method to evaluate blade deflection during operation of the rotor.

Development of the PIV-System

With standard PIV the velocity components of the vortex in the plane, as cut by the light sheet, are obtained in the form of a 2C-2D instantaneous velocity field. However, for complete understanding of the fluid mechanical phenomena as well as input to numerical simulations, exact information about the axial velocity component within the core of the tip vortex and its orientation in space (true diameter of vortex core) are required. This information can only be achieved by a 3C-2D stereoscopic PIV system. This PIV system is a new technology being developed under this contract. To adapt the stereoscopic approach at PIV as developed in laboratory to the Large Low-Speed Facility of the German Dutch Wind Tunnels (DNW-LLF) , a number of additional developments are necessary. First of all the optical access in wind tunnels rarely permits the imaging configuration to be symmetric as it is usually implemented for stereoscopic PIV. Another requirement is that the small seeding particles have to be imaged over large distances exceeding 9 meters. This makes the use of large focal length lenses with large light collecting capability (i.e. small f-numbers) necessary.

As the measurement precision of the out-of-plane velocity component increases as the opening angle between the two cameras reaches 90 degrees, it is necessary to mount the camera on a large, traversal common base. During investigations of helicopter rotors there is no access to the wind tunnel's test section: remote control of all elements of the focusing devices, the Scheimpflug adapter of the camera, the laser operation and the traversing systems is essential.

The most widespread implementation of the PIV method (standard 2C-2D PIV) images seeding particles suspended in the flow under investigation by illuminating them with a pulsed laser light sheet which is orientated normal to the imaging axis of the camera. The camera records the positions of the particles by stroboscopically illuminating the flow with at least two light pulses in short succession. By measuring the particle image displacement, either by particle tracking or locally applied statistical methods, the two-dimensional projection of the local velocity vector can be estimated using the magnification factor, M, and the laser pulse delay, $\Delta t = t - t'$. See Figure 1.

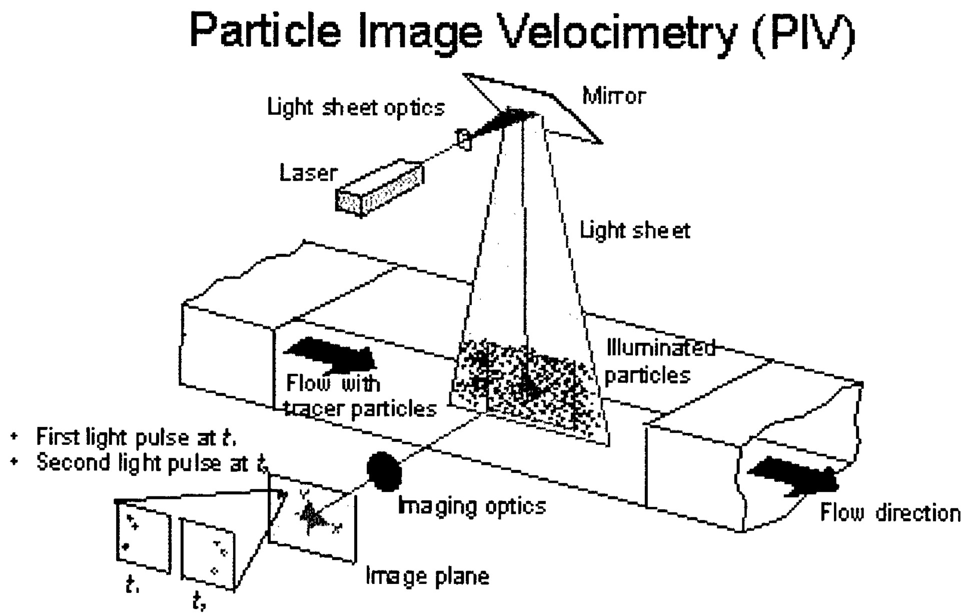


Figure 1: Experimental setup for PIV recordings in a wind tunnel.

In the past years the PIV method has gained continual acceptance as a valuable fluid mechanics research tool in a wide variety of applications. In most cases however, the method was employed in laboratory settings in which the set-up and data acquisition times were secondary with respect to obtaining high quality data. The principal aim of DNW's efforts was to provide PIV systems for application in a wide variety of their wind tunnel facilities. This imposed a number of additional requirements not present in typical laboratory environments:

- the PIV system has to be easily portable,
- its components need to be modular to adapt it to each tunnel's unique features,
- reliability and the ability of remote control of all critical components of the PIV system are of principal concern due to the high cost of operating large wind tunnels,
- the time between the actual PIV recording and the availability of the recovered PIV vector data sets has to be as short as possible (without reducing the quality of the data) in order to be able to rearrange the test program according to the results already obtained.

Based on the description of the measurement procedure as given above, DNW's PIV system will be described in the next sections.

Test-Setup of the System

For the study at the helicopter rotor the measurement equipment was arranged as shown in Figure 3. The two recording cameras were located at the mast, which is mounted onto the Common Support (CS) and placed in a vertical plane intersecting the observation area. The angle between the camera axes and the normal of the observation area was approximately 15°. Two sensitive and high spatial resolution CCD cameras have been used to image an area of 25 X 30 cm^2 over 7.5 m from each camera. The light source is a combination of two double oscillator laser systems, thus 2 x 2 x 320 mJ, see Figure 2.

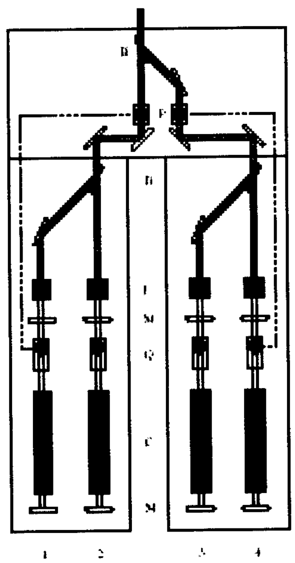


Figure 2: Beam combination of four single-pulsed and frequency-doubled Nd:YAG lasers. (M) mirrors of the resonator, (C) cavity, (Q) Q-switch, (F) frequency doubler, (B) Brewster window, (P) Pockels cell.

The CS can traverse the PIV-system along the X- and Y-axis of the wind tunnel co-ordinate system and it can rotate around the Z-axis. With the traversing range of the CS (2m in y-direction, 4m in x-direction) all measurement locations on either the advancing side or the retreating side can be covered in one wind tunnel run. In order to change sides the CS has to be moved to the corresponding opposite side. Figure 4 shows a photo of the PIV-system on the CS applied on the retreating side.

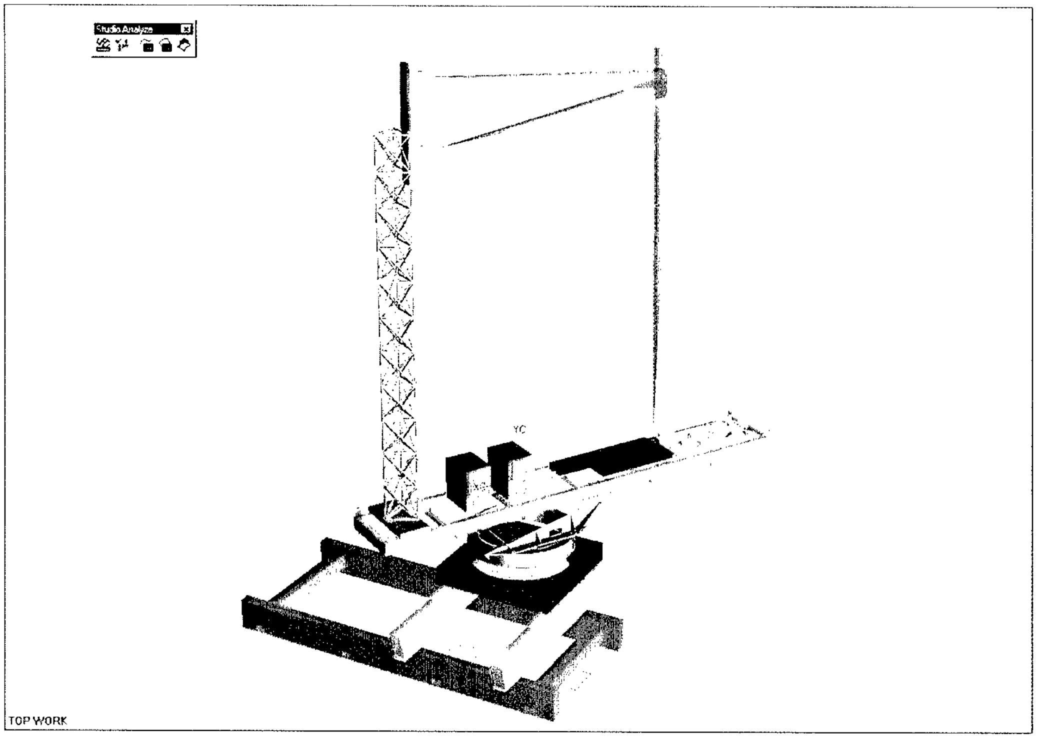


Figure 3: PIV-setup for measurements in the open-jet test-section of DNW-LLF.

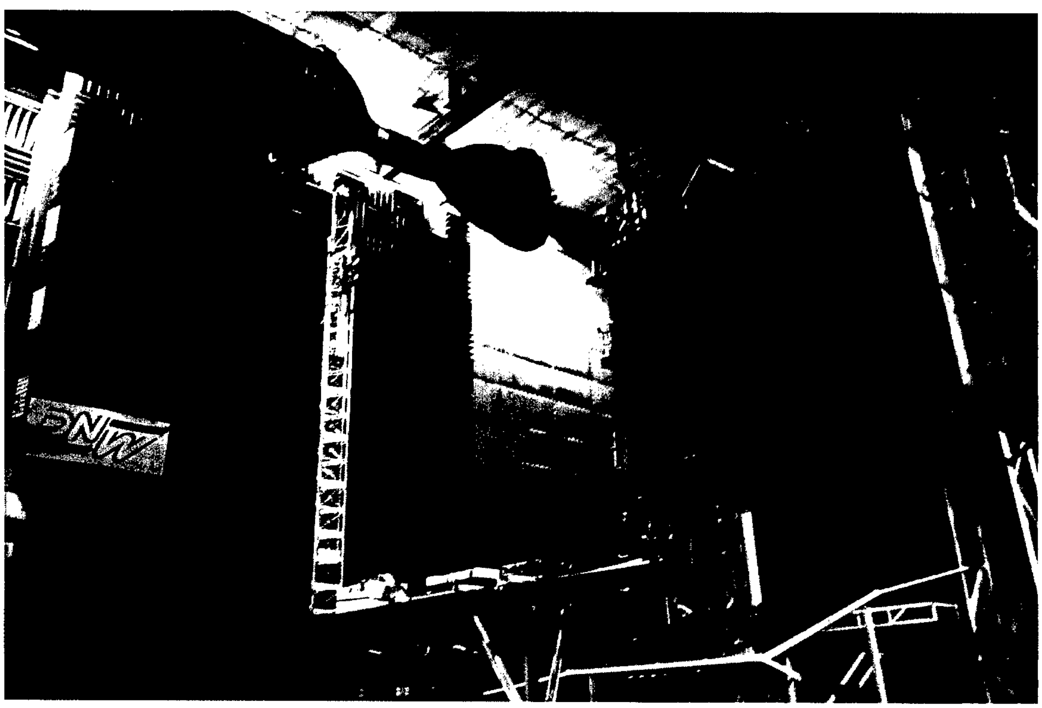


Figure 4: Common Support with PIV-System. Setup for measurements on the retreating side.

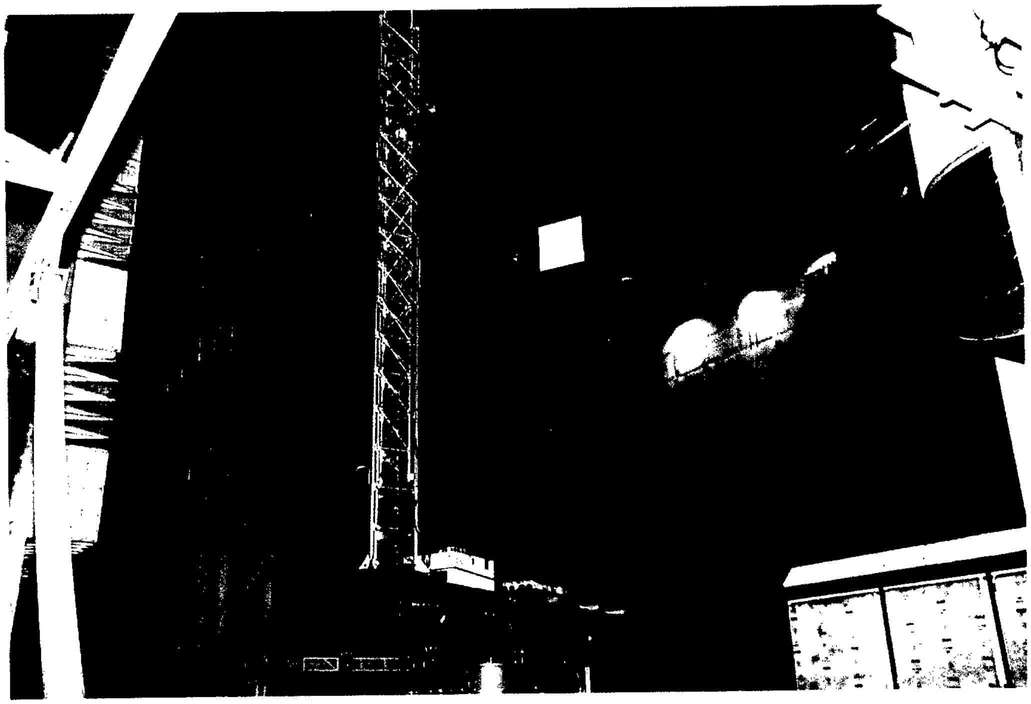


Figure 5: Setup for calibration of the PIV-System. The calibration grid is lifted into the area of interest by means of a telescopic mast.

PIV measurements require calibrations of the image scale (pixel per length unit) and the location (X-, Y- and Z-wind tunnel co-ordinates). For this purpose a calibration grid is lifted to the area of interest by means of a telescopic mast, see Figure 5. The PIV cameras recorded this grid in order to determine the above mentioned image scale. The position of the grid was measured by means of theodolites in order to determine the location of the PIV observation area in the test section of the wind tunnel.

For seeding the flow in the wind tunnel, a seeding system consisting of two aerosol generators and a movable, remote-controlled seeding rake was placed in the settling chamber. In order to obtain a set of velocity data without gaps, a high and uniform seeding density in the region of interest is required. According to statistical simulations, at least 10 pairs of particle images per interrogation window are required to apply statistical evaluation methods. Such a seeding density, which is equivalent to ≈ 5 particles/mm^3, under practical conditions must also be achieved in regions where strong recirculation or velocity gradients are present. The most common seeding particles for PIV investigation of gaseous flows are Di-2-Ethylhexyl-Sebacat (DEHS) droplets, which are generated by means of Laskin nozzles. Each aerosol generator contains 40 Laskin nozzles and produces oil particles, the aerodynamic diameter of which is about 1 μm. Switching four valves at the nozzle inlets can control the amount of particles. The particle concentration can be decreased by an additional air supply via the second air inlet.

Measurements of Rotor Velocity Field

The velocity field of several cross sections normal to the vortex lines of all main rotor blades at different locations on the advancing side as well as on the retreating side was measured to understand the rotor noise generating mechanisms. This measurement sequence has to be repeated for different rotor configurations and for different instantaneous azimuth angles of the rotor blades. An example of measurement locations for one rotor condition is depicted in Figure 6.

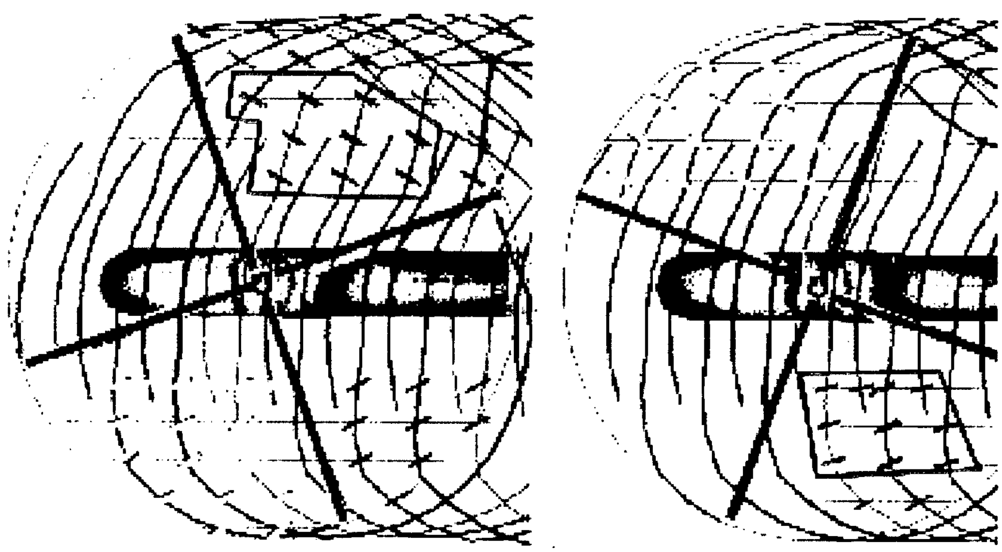


Figure 6: Top-view on measurement locations for PIV on advancing and retreating side. Left graphic shows locations for blade #1 fixed at $\Psi = 20°$, right graphic shows location for blade #1 fixed at $\Psi = 70°$.

The actual location of the vortices, which have to be measured, has been determined by means of flow visualization using the LLS technique. Flow visualization has been proved as an excellent tool for determination of phenomenon locations and for better understanding of flow behavior. An example of a flow visualization image is shown in Figure 7.

Figure 7: Double vortex, generated by a helicopter rotor blade.

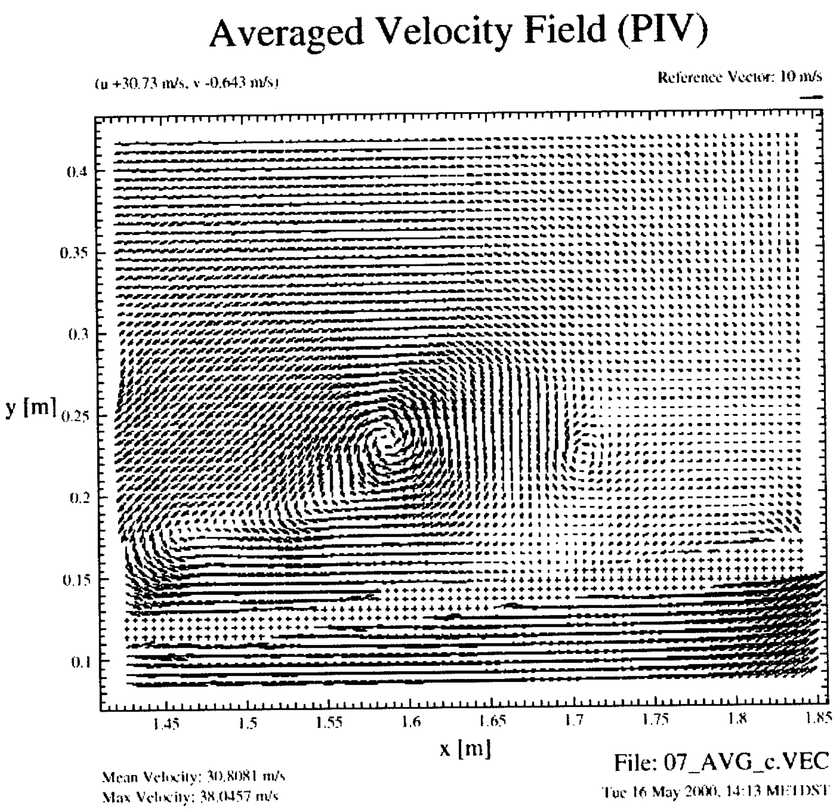


Figure 8: Two-component vector map of the flow-field of a double vortex.

The velocity field in general and the tangential velocity in particular have been measured. Figure 8 shows an example of a flow velocity field as obtained during this test. The rotor blade tip, which had just passed the observation area (light sheet plane) when the recording was taken, generated the vortex pair present in Figure 8. The vector map confirms the conclusion made with the aid of the flow visualization image that this vortex pair consists of counter-rotating vortices.

A three-component result of another vortex and the corresponding flow visualization image are shown in Figure 10 and Figure 9 respectively. The graphic within Figure 10 presents the transverse, the normal and the axial component of the velocity along a line indicated in the vector plot. Especially the axial velocity component shows strong spatial gradients. This axial velocity component is of special interest for the understanding of rotor tip vortices.

Figure 9: Flow visualization image. The frame indicates the area, where a three-component velocity field has been measured by means of PIV, shown in Figure 10.

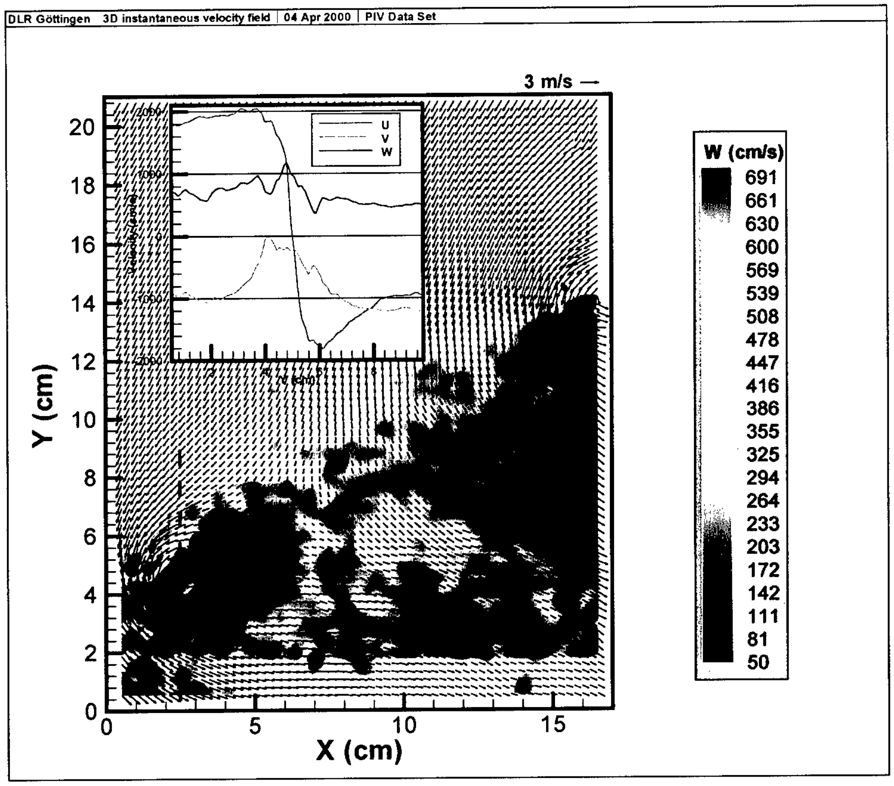


Figure 10: Three-component vector map of the vortex shown in Figure 9.

LLS Technique

Flow visualization by means of the laser light sheet (LLS) was applied to the model rotor. It was the task to spatially analyze the obtained video images. Main objective was to obtain the geometry of selected wake vortex filaments relative to the position of the blade at a given blade azimuthal location. In order to show if one or multiple vortices are produced of the rotor measurements at different rotor conditions were executed. In order to make efficiently use of the available test time, LLS- and PIV-measurements were performed with the same set-up of lasers and seeding system.

LLS-Setup

As mentioned above, the investigation area for LLS and PIV was the advancing side of the rotor as well as the retreating side. Compared to PIV, a larger (wider) light sheet was adjusted for LLS in order to record several adjacent vortex cross sections and at least one rotor blade in one video image. Furthermore, for LLS a wide-angle lens was connected to the digital camera. However the viewing position of this camera was the same as for PIV. During the LLS test the cameras used for PIV were not in operation. The requested cross sections were obtained by traversing the light sheet in flow direction (x-direction) through the corresponding area step by step. The step length was about 0.4 m; the total traversing length was 3.6 m. The field of view of the LLS camera was adjusted in such a way that the entire width of the light sheet at every traversing position was visible.

The measurement technique used for LLS was the same as described in the PIV chapter. All components were identical to the PIV system.

LLS Measurements and Results

A large number of data points were measured during the test at different rotor settings and corresponding wind tunnel conditions. Examples of flow visualization images are represented in Figures 7, 9, 11 and 12. Each data point consists of an image sequence of at least 200 frames (about 1 minute recording time). The position of the image plane was defined by a calibration plate, which was placed where the measurement was carried out. The light sheet was adjusted to be within the front side of the plate. From the calibration image, the image magnification as well as the absolute location within the rotor coordinate system could be derived by means of theodolites. The position change caused by traversing the light sheet could be calculated by adding the traverse read-out directly to the original x-position (calibration position). This was possible, because the light sheet traverse was aligned parallel to the x-axis of the rotor coordinate system.

The position of the center of each vortex cross section was determined by means of instantaneous flow visualization images. The recorded video images were analyzed by especially developed image processing software.

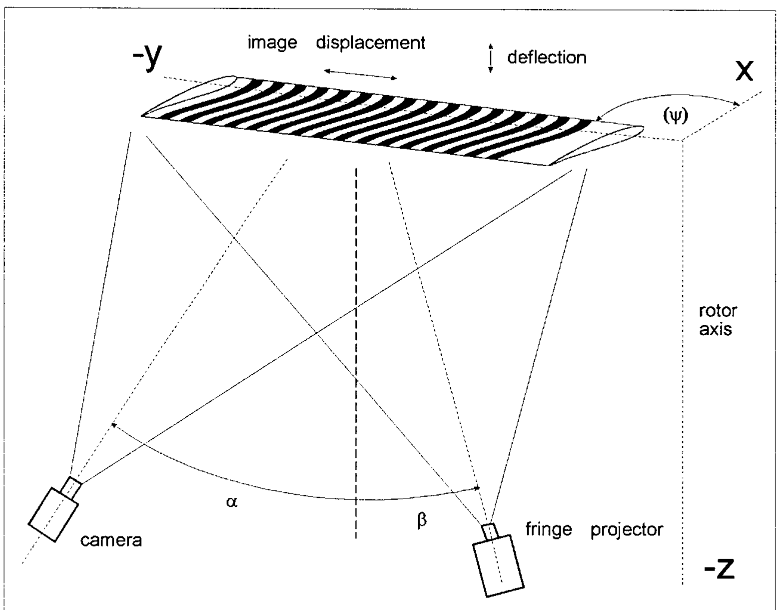
Figure 11: Flow visualization image obtained by LLS on the advancing side of the rotor. The white dots represent the vortex center. The most right one indicates a young vortex, which is generated by the blade in the background

Figure 12: Flow visualization image obtained by LLS on the retreating side of the rotor. The white dots represent the vortex center. The most left one indicates a young vortex, which is generated by the blade tip in the foreground right.

The Projected Grid Method (PGM)

The principle method is the so-called projected grid method, where a grid is projected on a blade surface, which is deformed, or displaced out-of plane. Viewing from a direction, which differs from the projection direction, the displacement of the blade can be evaluated. Comparing the variation of the grid pattern with a known reference case can then assess the torsional and flapwise deformation of the blade. The principles of this technique can be taken from Figure 13. The exposure time of the video camera is 10^{-5} s which revealed a blade movement of 2.1 mm during recording for a rotor-rpm of 1000 and a rotor diameter of 4.0 m.

The application of this method for operating rotors requires that the blades are painted dull white and the test hall is darkened. The recordings of the blade in motion were carried out by a triggerable high resolution CCD camera that was synchronized with the rpm indicator of the rotor. Furthermore, the grid images were processed separately and subsequently the results of the separate digital image processing were subtracted from each other in order to obtain quantitative information with respect to the rotor center. In this way, pre-twist of the blade was automatically taken care of. For reference the projected grid was also recorded at the desired azimuthal angle with the rotor standing still. Therefore the blades were adjusted on a perfect horizontal level at an azimuthal angle of 90°. The tip deflection due to the weight of the blade was then less than 1 mm. In order to assess the reference to the rotor center, the position of the blade tip was measured with a theodolite. The same procedure was followed for all other azimuthal angles.



deflection = (cos β / sin(α + β)) * image displacement

Figure 13: Principle of PGM applied to rotor systems.

Additionally, for easier data interpretation the grid was projected perpendicular to the leading edge of the blades. The projection of the grid in this way yields, that a parallel shift of the grid pattern is equivalent to a vertical displacement of the blade, whereas a skewed shift of the grid lines occurs due to blade torsion. This was achieved by installing a specially constructed optical bench underneath the rotor. The optical bench was equipped with the grid projector, the video camera and could be rotated over 360° with the center of the rotor aligned vertically with the center of the bench. At a pre-selected fixed position recording of the grid pattern was possible by triggering the camera with the rotor rpm and by adjusting the rotor phase shifter to the desired azimuthal angle of the optical bench.

Conclusion

Two-component and three-component PIV measurements of the wake of a helicopter rotor have been developed and also performed successfully in the open-jet configuration of the DNW-LLF. The test setup on the common support traversing system has been proved as the best suited with respect to the requirements of complex rotor velocity measurements. By application of stereoscopic PIV it is now possible to obtain the third velocity component as well. The axial velocity component is of special interest for the understanding of rotor tip vortices. If, as it is mostly the case, these vortices exhibit an unsteady behavior, the only possibility to measure the velocity field conclusively with all three components is by application of stereoscopic PIV.

The flow visualization technique LLS and the blade deformation technique PGM were also successfully applied and completed the data set with important information about vortex core positions and blade deformation.

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